RESEARCH AND DEVELOPMENT TECHNICAL REPORT
CECOM-TR-96-6

Step Potential Modification by the Lightning Electromagnetic Environment

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September 1996

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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1996

3. REPORT TYPE AND DATES COVERED
Technical Report

4. TITLE AND SUBTITLE
STEP POTENTIAL MODIFICATION BY THE LIGHTNING ELECTROMAGNETIC ENVIRONMENT

5. FUNDING NUMBERS

6. AUTHOR(S)
John M. Tobias

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
US Army Communications-Electronic Command (CECOM)
CECOM Safety Office
ATTN: AMSEL-SF-SEP
Fort Monmouth, NJ 07703-5024

8. PERFORMING ORGANIZATION REPORT NUMBER
CECOM-TR-96-6

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The purpose of this report is to introduce a modified theory of propagation for lightning currents in earth. Recent experimental evidence has pointed to modified current flow distributions near earth grounding systems subjected to natural electric fields in excess of the fine weather electric field. Current distributions in earth due to lightning discharges are of interest to safety professionals due to the development of the step potential. This step potential examination considers the space charge region developed in the earth as a consequence of the charge present in a thunderstorm cloud. It is theorized that, under certain conditions, the step potential may be significantly higher than previous theoretical estimates, or empirical results obtained under fine weather electric field conditions. The objective of this report is to present the theory of the influence of the cloud charge on current distribution and, hence, step potential by citing recent qualitative observations of rocket-triggered lightning studies. Behavioral description of the step potential will be developed from electromagnetic theory. Impact of the modified step potential on personnel electrical hazards will be discussed. The presentation concludes with suggestions for further research in this area.

14. SUBJECT TERMS
Lightning; grounding; electrical grounding; step potential

15. NUMBER IF PAGES
13

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

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Step Potential Modification by the Lightning Electromagnetic Environment

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Abstract

The purpose of this report is to introduce a modified theory of propagation for lightning currents in earth. Recent experimental evidence has pointed to modified current flow distributions near earth grounding systems subjected to natural electric fields in excess of the fine weather electric field. Current distributions in earth due to lightning discharges are of interest to safety professionals due to the development of the step potential. This examination of the step potential considers the space charge region developed in the earth as a consequence of the charge present in a thunderstorm cloud. It is theorized, that under certain conditions, the step potential may be significantly higher than previous theoretical estimates, or empirical results obtained under fine weather electric field conditions. The objective of the report is to present the theory of the influence of the cloud charge on current distribution and, hence, step potential by citing recent qualitative observations of rocket-triggered lightning studies. Behavioral description of the step potential will be developed from electromagnetic theory. Impact of the modified step potential on personnel electrical hazards will be discussed. The presentation will conclude with suggestions for further research in this area.

Introduction

Step potentials are a well known phenomena arising from the dissipation of lightning current in the earth. In this report, a theory that attempts to explain observations of lightning current traveling on the earth's surface, sometimes in preferred directions, is presented. To begin, we will characterize step potential, lightning events, the nature of space charge in the thunderstorm clouds, and space charge effects on earth.

Step Potential

A voltage gradient exists as a function of distance from the ground rod. Therefore, we can expect a significant voltage difference near an earth electrode system undergoing current injection. This is known as the **step potential**, named after the potential drop across human (or animal) feet in the space of a step. Step potential developed from lightning effects, or even large fault currents, can be lethal. Figure 1 illustrates the hazards from step potential. The current is injected in the center of figure 1, and the resulting potential difference between x and x+step length is the highest at that point. We can see in figure 1 that step potential is dependent on step length, making it a greater hazard to the farm animal pictured.

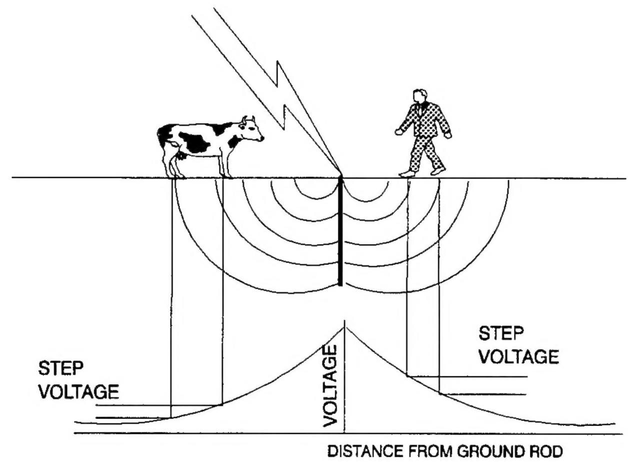

Figure 1. Step potential from a cloud-to-ground lightning strike.

Lightning Characteristics

Lightning is essentially charge being transferred between space charge regions. Several types of lightning exist but our discussion will be restricted to cloud-to-ground negative lightning, which is the most common event (cloud-to-ground) encountered. Lightning propagation external to the cloud in this case is initiated by a downward moving negatively charged stepped leader. This leader is visible as a faintly luminous jagged line extending from the cloud toward earth. Propagation of the downward leader is measured typically in tenths of milliseconds. As the leader nears the earth a strong electric field is developed under it, initiating an upward moving positive leader. Attachment occurs when these leaders meet and initiate the lightning flash. Within the lightning flash, several current strokes may occur. There are typically 2-4 strokes per flash, but as many as 26 have been recorded.

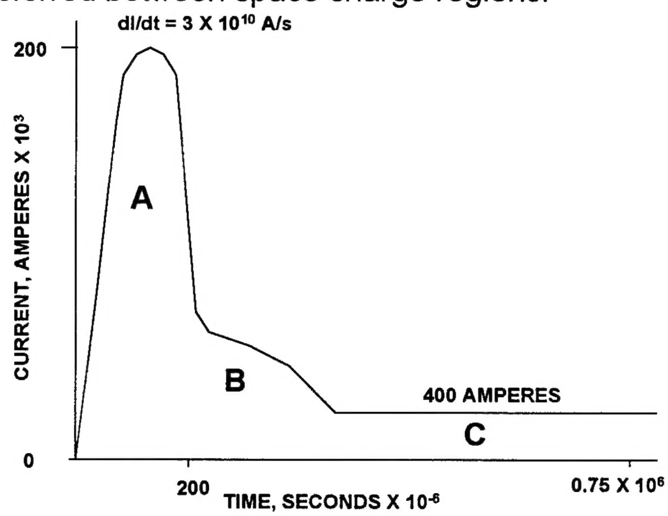

Figure 2. Typical Lightning Waveform. The x-axis scale is adjusted to highlight the A component high current pulse.

We can characterize the lightning by using a waveform model. The lightning pulse in figure 2 is divided into three parts, components A to C. Component A is the high-current pulse. It is a direct current transient that has been recorded to reach up to 260,000 amperes and last for a duration of up to 200 microseconds. On the average, it will reach 20,000 amperes for a 50-microsecond duration. Strikes above 200,000 amperes are considered rare. Component B is a transition phase on the order of several thousand amperes. Component C is a continuing current of approximately 300-500 amperes that lasts up to 0.75 second. A final component, D (not illustrated), is a restrike surge that is typically half that of component A in a given strike. It has generally the same duration as component A. Typically, 3 or 4 restrikes will occur in one lightning event but the maximum observed is 26 restrikes in **one** lightning event. Sources differ on the magnitude of D; some state all restrikes are one-half the magnitude of the A component and some sources imply that the D component continually decreases by one-half (e.g., 1/2A, 1/4A, 1/8A, etc.).

Cloud Charge Parameters and The Electric Field

Charge is distributed within a cloud in thunderstorm conditions causing an increased electric field in the vicinity of the cloud. For our purposes, we are only interested in the specific distribution of charge within the cloud as it affects the resultant electric field. First, consider the basic charge distribution model given by Uman (Ref.1) in figure 3. The charge is distributed into three points called the P, N and p regions. Typical values for each are P= 40 coulombs, N=-40 coulombs and p=10 coulombs. Each makes a contribution to the resultant field observed from the ground as a function of its magnitude and distance above the ground. Under normal conditions there is a small electric field of approximately 100 volts/meter magnitude at ground level, called the fair weather field. It is usually referred to as a positive field, meaning that the field direction is downward resulting from a positive charge above the earth's surface. During thunderstorm conditions, where the charge distribution is as illustrated in figure 3, the electric field at ground level is significantly modified. Using typical values of p = 10 coulombs, the resultant electric field magnitude at ground level as a function of distance from the thundercloud is given in figure 4 (Ref.1). Note that the field polarity is reversed, that is, the field is now directed upward. Directly under the thundercloud a

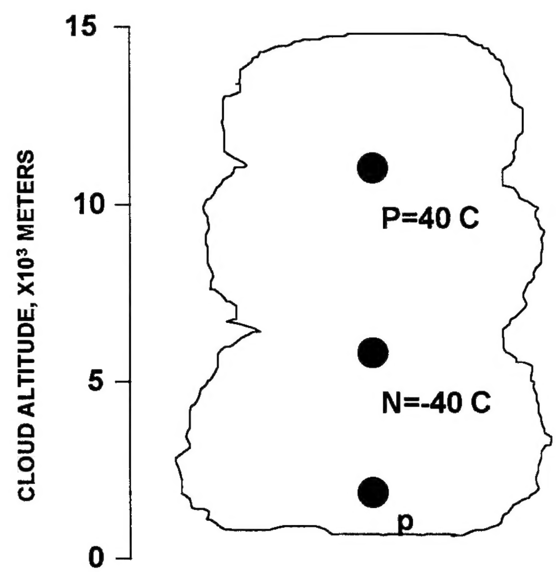

Figure 3. Typical charge distribution in a thundercloud.

field of several tens of thousands of volts per meter can be developed, which represents several orders of magnitude change from the fair weather field magnitude.

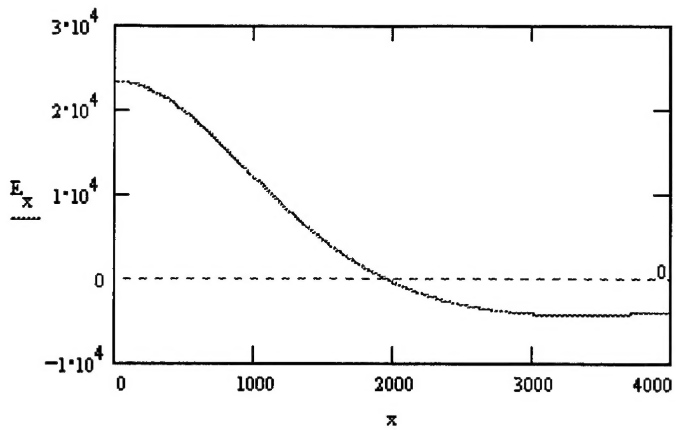

Figure 4. Electric field (volts/meter) magnitude as a function of distance on the earth's surface (meters) under the thundercloud charge distribution.

Electric Field Induced by Lightning Propagation

The lightning event lowers a portion of the thundercloud charge to earth. During this process, the field on the earth's surface is significantly modified by the approaching leader. This process can also be described by an electrostatic model using the results presented by Uman (Ref.1), which we illustrate in figure 5.

Our interest is in the local electric field conditions on the earth's surface in the vicinity of the strike location. Using the electrostatic model illustrated in figure 5, we can plot the electric field (using typical values during the approach of the leader) as a function of distance (horizontally along the earth's surface) away from the leader. This field enhancement is above that of the field enhancement due to the thundercloud. Note from figure 5, that this field enhancement can be up to six orders of magnitude higher than the surrounding region.

From studying the electromagnetics of the environment near the leader on a qualitative

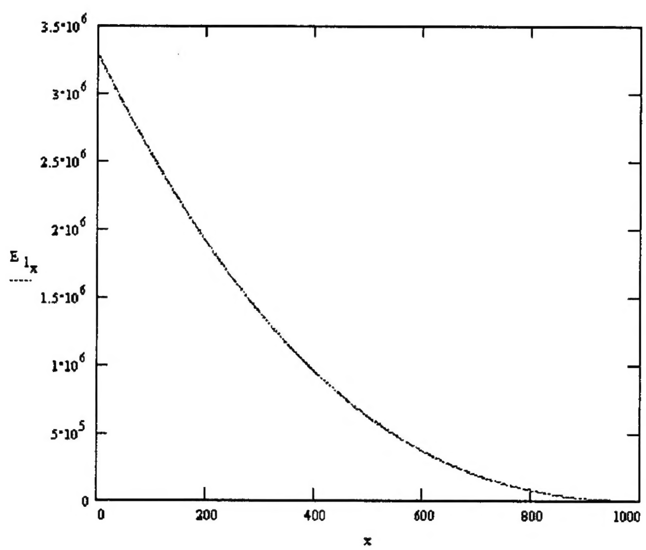

Figure 5. Electric field magnitude enhancement (volts/meter) along the earth's surface (meters) due to approaching leader .

basis, we conclude that very significant increases (or decreases, depending on th polarity of the lowered charge) occur.

Field Interaction With the Earth

To begin with our theory of interaction, we compare the earth to the semiconductor class of materials. The basis of comparison is that of resistivity or conductivity. In typical earth, as in semiconductors, the resistivity, which is a material property, can vary widely depending on several factors, such as impurities introduced. Fundamentally, the importance of this is the basis for development of a space charge region in the soil. Another basis for comparison is the well known fact that the introduction of ionic salts into the soil, or earth, modifies the electrical property of conductivity or resistivity. A chemical process of ionization occurs where the chemical salt added to the soil, for instance, sodium chloride or common table salt, encounters the moisture present in the soil. Ionization (from this process and possibly others) modifies the conductivity according to the relation:

$$\sigma = n \cdot q \cdot \mu = \rho_{\text{charge}} \cdot \mu \qquad \text{(eq.1)}$$

where n = number of ionic charges per unit volume; q = elemental charge, 1.6×10^{-19} coulombs, and μ = mobility which is a constant that depends on the material properties of the soil (or semiconductor). It is defined as $V = \mu E$, the velocity of a charge carrier like an electron developed in the presence of a known electric field, E. We note that $nq = \rho_{charge}$, which is the charge density in units of coulombs per unit volume. Having established the relation between soil ionization and conductivity, let's examine the interaction of the electric field.

Using the Poisson equation, we can derive a relation between the field and the ionization. Using an approximation (sometimes called the depletion approximation) of complete ionization in a given region for a particular ionizable impurity, we can write the Poisson equation:

$$\nabla^2 \Phi = -\frac{\rho_{\text{charge}}}{\varepsilon} \qquad \text{(eq.2)}$$

which means that the del squared operator applied to the electric potential (or, since this is a one dimensional case, the second derivative of the electric potential with respect to the distance, x) is equal to the negative of the charge density, ρ, divided by the electric permittivity, ε.

Let's apply this to a model of the electric field/earth interface as illustrated in figure 6. We can establish that ρ_{charge} = qn where we said that n is the number of ionizable carriers in the soil. We then substitute, apply the one-dimensional condition mentioned and integrate:

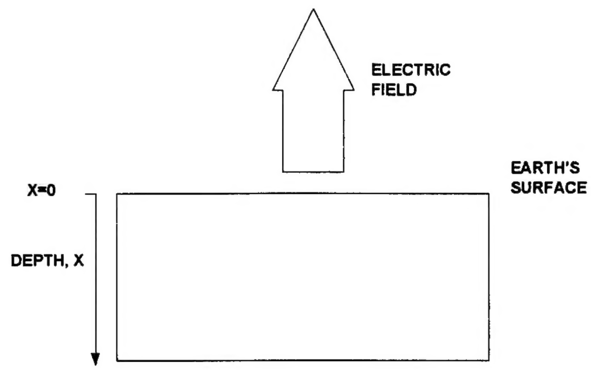

Figure 6. Electric field / earth surface model.

$$\int \frac{d^2V}{dx^2} dx = \int_x^W -\frac{qn}{\varepsilon} dx \qquad \text{(eq.3)}$$

yielding:

$$\frac{dV}{dx} = E = -\frac{qn}{\varepsilon} \cdot (x - W) \qquad \text{(eq.4)}$$

where dV/dx is the first derivative of the electric potential with respect to depth, x, or simply the electric field. W is an arbitrary depth in the soil. Several items can be deduced from this equation. First, the electric field as a function of depth in the soil is linear and decreasing with depth. The maximum is reached at the earth/air interface and decreases until it reaches zero at x = W. If we are interested in finding W we can examine E(x = 0) and rearrange the equation:

$$\frac{\varepsilon \cdot E(x=0)}{qn} = W \qquad \text{(eq.5)}$$

What this implies is that there exists a density of ionic charges, n, that is constant to a given depth, W, in response to some electric field, E, at the earth's surface. Hence there exists a charge density, ρ_{charge} or a space charge region. Lets redraw our model in figure 7, illustrating the field magnitude and the space charge. On the left, we have in the -x, or air, region a constant electric field that represents the field induced by the approaching leader. At the air/earth interface there is a discontinuity to account for the change in ε, the electric permittivity. In the air region

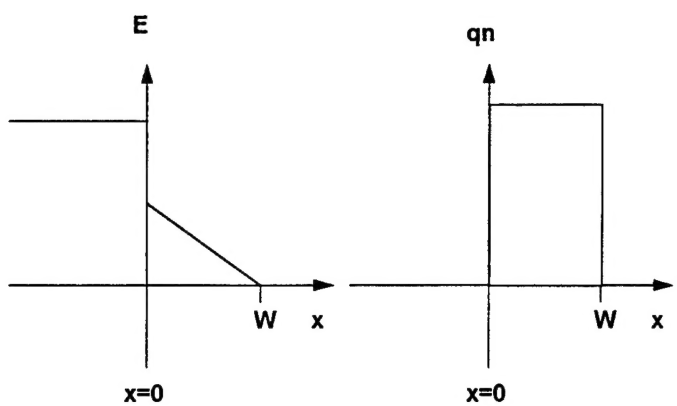

Figure 7. Electric field magnitude and charge distribution near earth's surface in presence of a constant electric field. (not to scale)

the relative electric permittivity equals unity, while in the earth it is likely 10 or great depending on the local conditions. Since we have deduced the existence of a spac charge region near the earth's surface we can further deduce that the conductivity of this region is significantly changed.

Using the typical numbers cited for thunderstorm cloud conditions, we can guess at the depth of W within an order of magnitude or so. Let's guess (since we do not know the mobility, μ) that for soil that is somewhat conductive, the number of ionic carriers can be approximately $n = 10^{17}$ carriers per cubic meter under electric field conditions, $E = 10^6$ volts/meter. Suppose this corresponds to soil having a conductivity of 0.1 siemens per meter (since conductivity is the reciprocal of resistivity, this is equivalent to a soil of resistivity equal to 10 ohm-meters or 1000 ohm-centimeters), which is considered to be fairly conductive. We can then guess at the mobility: $\mu = 6.25\ m^2/V\text{-sec}$. To check if this is realistic, use $\mu E = V$, where we recall V is the electronic carrier velocity under some electric field. In this case, $V = 6.25X10^6$ meters/second, which is well below the speed of light, $3X10^8$ meters/second, so we know our approximation has some validity. Using this approximate value, we calculate from the equations presented that $W \cong 5.5X10^{-3}$ meters or approximately 5 to 6 millimeters. From the expected field magnitudes illustrated in figure 5, we can expect a region of highly increased conductivity for tens or possibly hundreds of meters from the point directly under the advancing leader. One assumption we have made is that the soil medium is completely uniform in composition. This is not true in almost any physical case. With variation in soil composition, we might expect an irregular distribution of enhanced conductivity. We will not further consider this possibility here, as modeling it is beyond the scope of this report.

Modification of the Surface Current Under Lightning Conditions

With the expectation that a thin highly conductive region exists surrounding the point where a downward lightning leader impacts the ground, we note that this is similar to a thin sheet of metal on the earth's surface. Under this approximation, we then expect that the current developed from the lightning leader impacting the earth will then preferentially travel in this thin, highly conductive region. We expect that the thin sheet phenomena will occur for a short time following the strike, since the electric field will decrease rapidly once the lightning discharge has begun.

Experimental evidence deducing the existence of the thin, highly conductive surface layer exists. During experiments utilizing rocket-triggered lightning, researchers from the U.S. Army Armaments Research, Development and Engineering Center and Sandia National Laboratory observed this phenomena (Ref.2). They concluded that the current was flowing in a "sheet mode" within 10 and 20 meters from the injection point and that the step potentials exhibit a $1/r$ variance as opposed to a $1/r^2$ variance (r = distance from the injection point along the earth's surface) which is usually predicted.

This is supported by our predicted electric field in figure 5, which is nearly linear with respect to the earth's surface out to approximately 500 meters, after which it appears to assume a quadratic form. As the electric field decreases linearly with distance away from the point of lightning strike to the earth, the depth of the space charge region in the earth should also decrease linearly, explaining the experimental observation.

If the step potential exhibits a 1/r dependence, it might be concluded that the hazard is decreased as the potential drop is less per unit distance. In our approximation that the highly conductive region is similar to a metallic sheet on the earth's surface, we expect that the potential would be less since all points on the sheet would be approximately equipotential. However, as we have mentioned, the soil medium is nonuniform and since the current may flow in preferential radial directions, the step potential may in fact be more hazardous due to the significantly increased current (Ref.2). If the current is flowing in a very thin sheet on the surface, or in preferential radial directions, we might also expect increased corona and flashover phenomena, which may increase ignition hazards to nearby structures.

Topics for Further Study

Additional experimentation is needed to validate this theory and to further characterize the interaction of the lightning with the ground. Characterization of the soil material properties, such as the permittivity and mobility, must be made in order to produce accurate calculations. The interaction of the lightning discharge with grounding systems must also be reexamined in light of this new information. Traditional grounding systems using ground rods might be less effective than thought in dissipating lightning current. Initial investigations (Ref.3) suggest that ground rods and counterpoises may not be as effective as once thought for lightning phenomena. The difficulty in conducting these studies is that the ambient electric field environment must simulate that found under lightning conditions. Simple current injection into the ground under fair weather field conditions will not be realistic in producing this phenomena. This practically limits the experiment to using either natural lightning phenomena or rocket triggered lightning for adequate results.

Conclusion

A theory describing the interaction of the lightning electromagnetic environment that affects the distribution of current discharge on the earth's surface has been described. This theory explains novel and unique experimental observations recently made. Under lightning conditions, the current distribution on the earth's surface is redirected to the surface by the presence of a thin, highly conductive space charge region. The observed 1/r dependence along the earth's surface is validated theoretically by the linear nature of the field magnitude as a function of distance from the downward

propagating lightning leader. Reexamination of current knowledge concerning step potentials and grounding systems is warranted in light of these results.

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